Ultimate Space Charge and its Compensation with e-Lens

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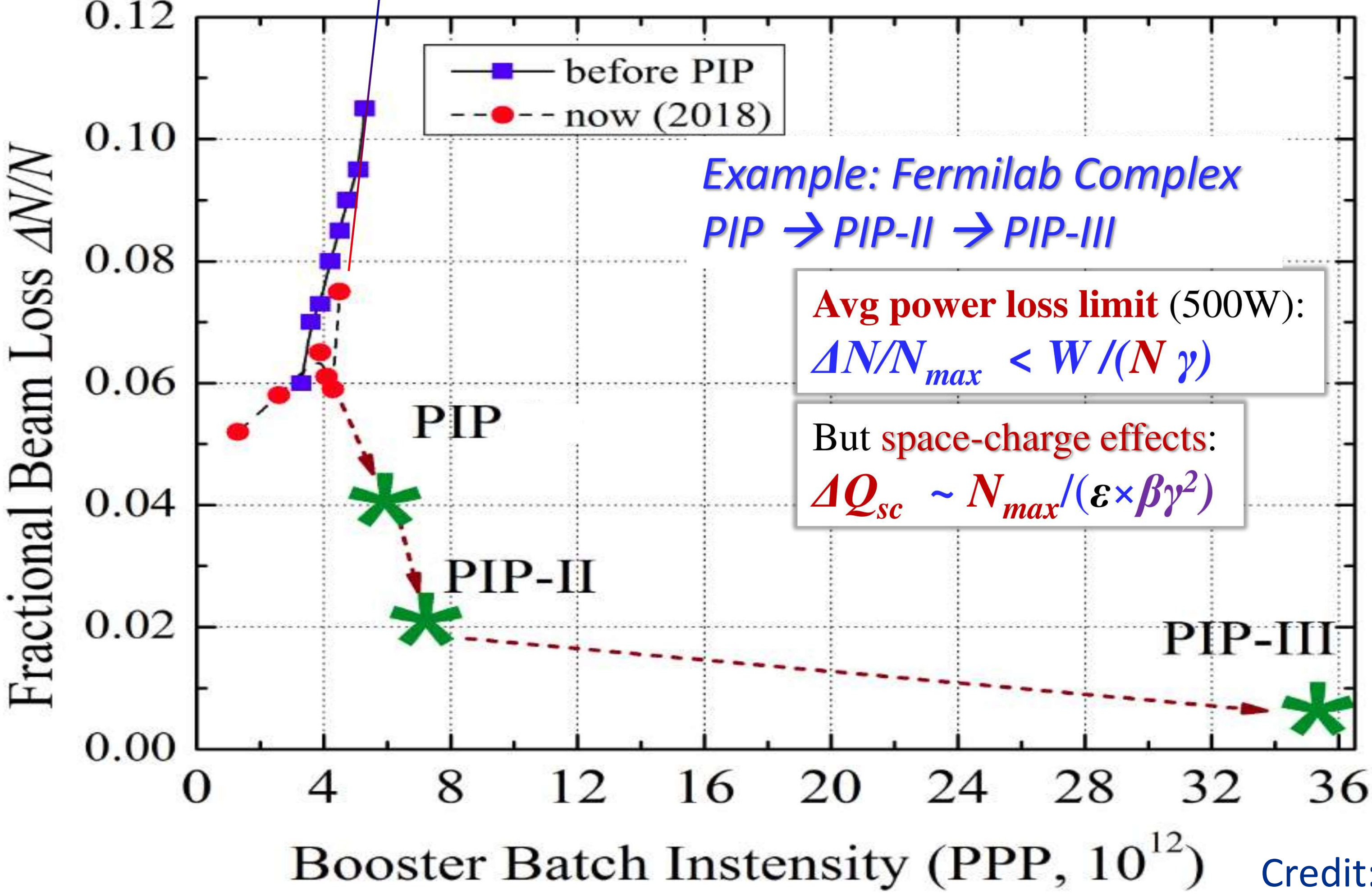
Accelerator Science & Technology Seminar

20 August 2019

Outline

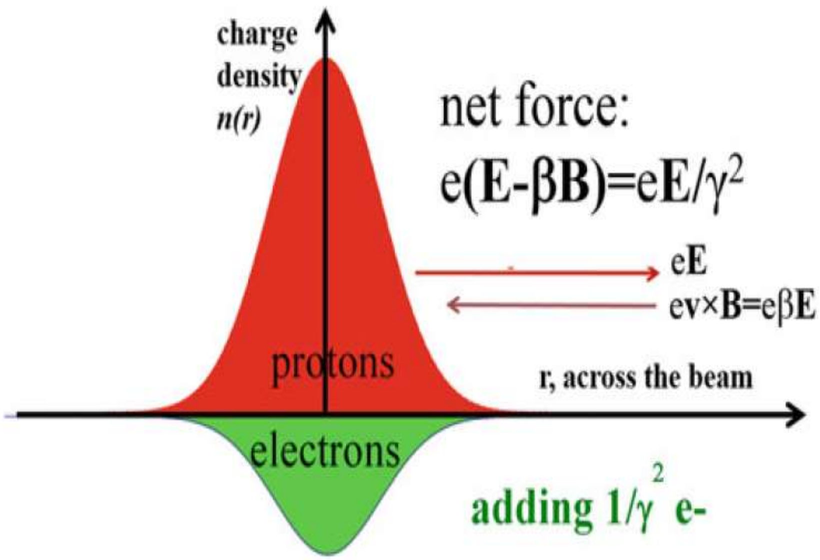
- Space Charge Effects and Compensation
- Evaluation Plan
- Simulation Codes
- Compensation Results Ideal Lens
- Compensation Results “Realistic” Lens
- Future Plans and Summary

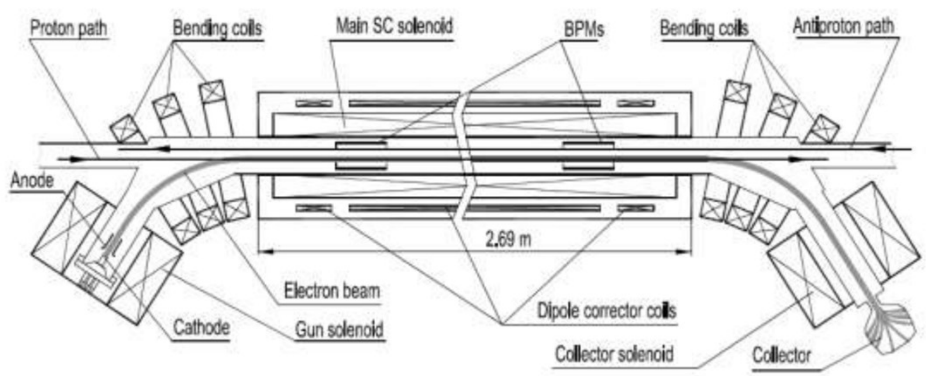
Protons Per Pulse Challenge: to lower beam losses while increasing intensity



Credit: Shiltsev

Space Charge and e-Lens Compensation

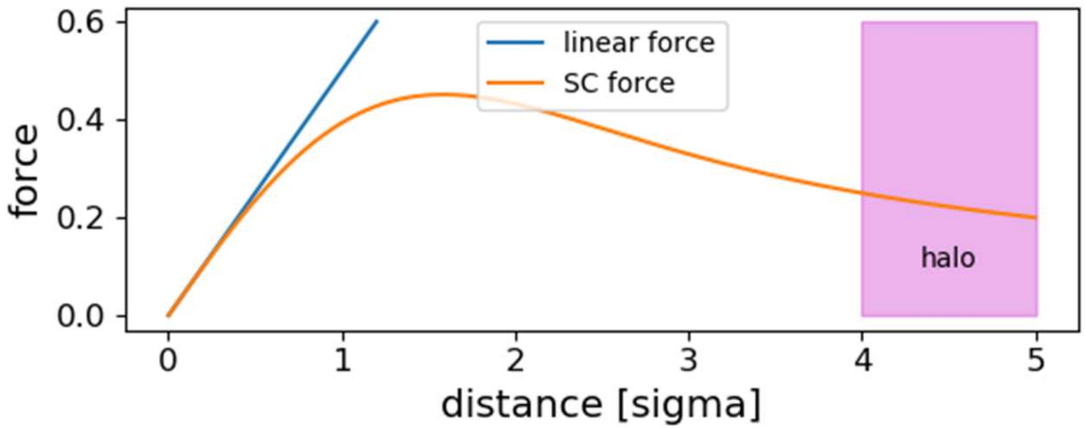




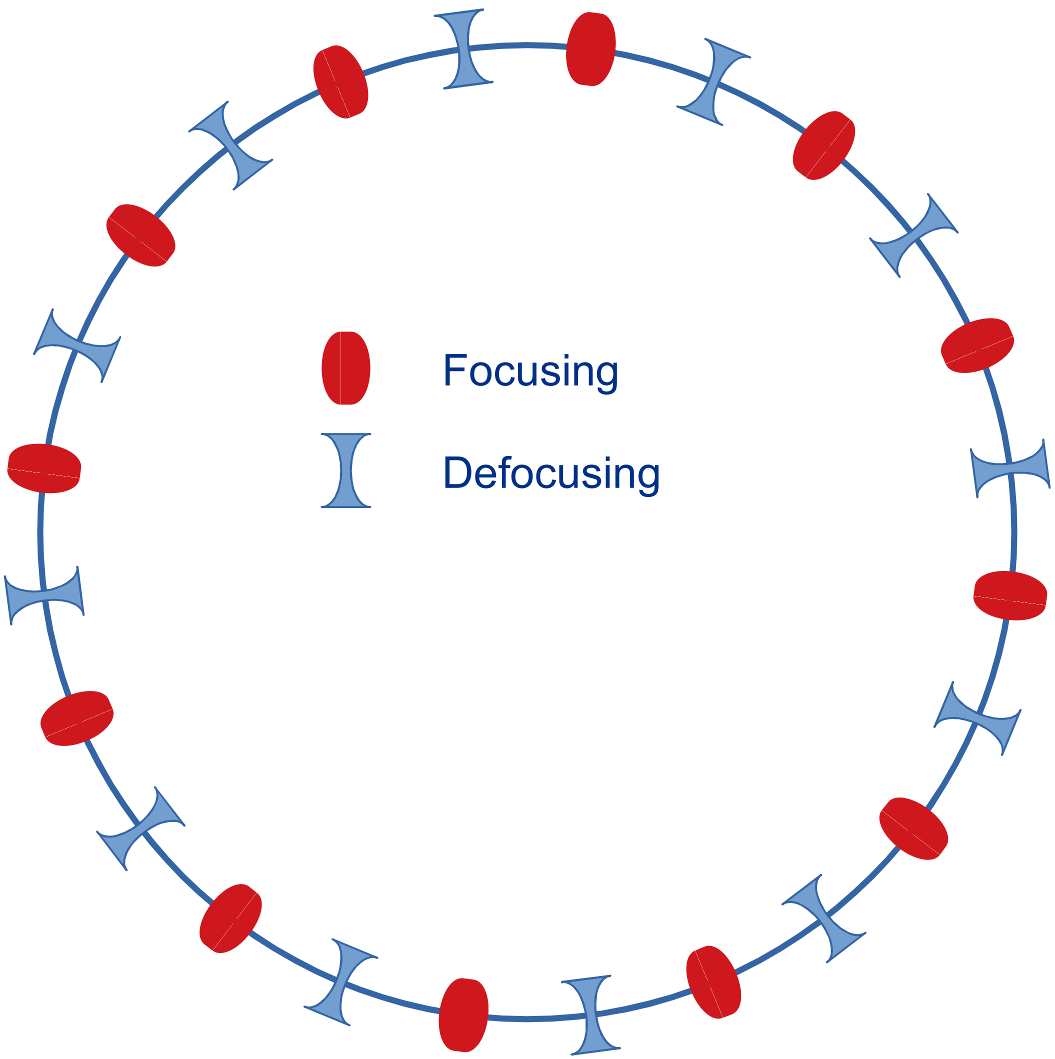
Space Charge and Electron Lens Forces

$$F(r)_{\mathrm{SC}} = +\frac{2I_p r_p}{e\beta_p^3\gamma_p^3 c}(1 - e^{-\frac{r^2}{2\sigma^2}})\frac{1}{r} \qquad \propto \frac{r}{2\sigma^2} \text{ for } r/\sigma < 0.4$$

$$F(r)_{\mathrm{lens}} = -\frac{2I_e r_p(1+\beta_e\beta_p)}{e\beta_e\beta_p^2\gamma_p c}(1 - e^{-\frac{r^2}{2\sigma^2}})\frac{1}{r}$$



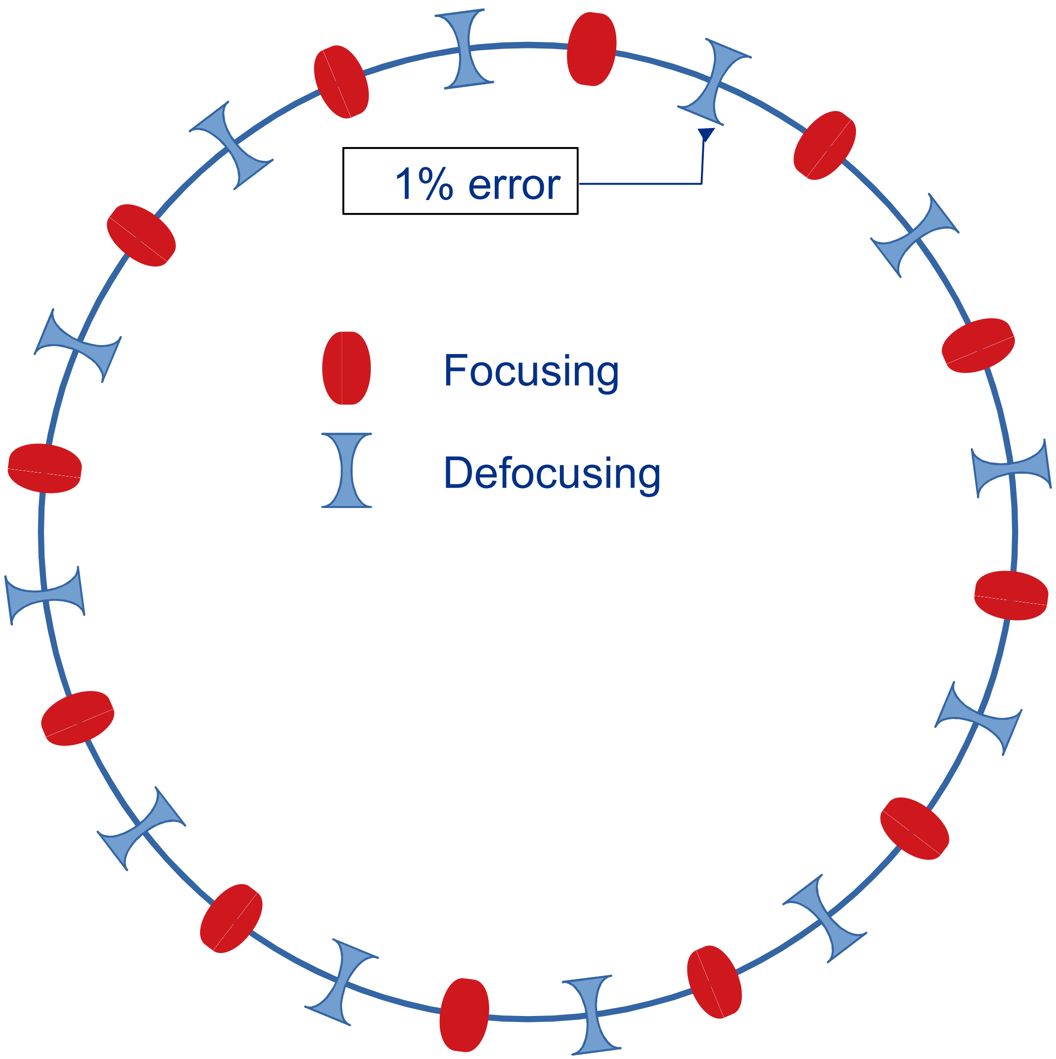
Evaluation Plan case #1



1000 turns

$dQ_{SC} = -0.9$

Evaluation Plan case #2

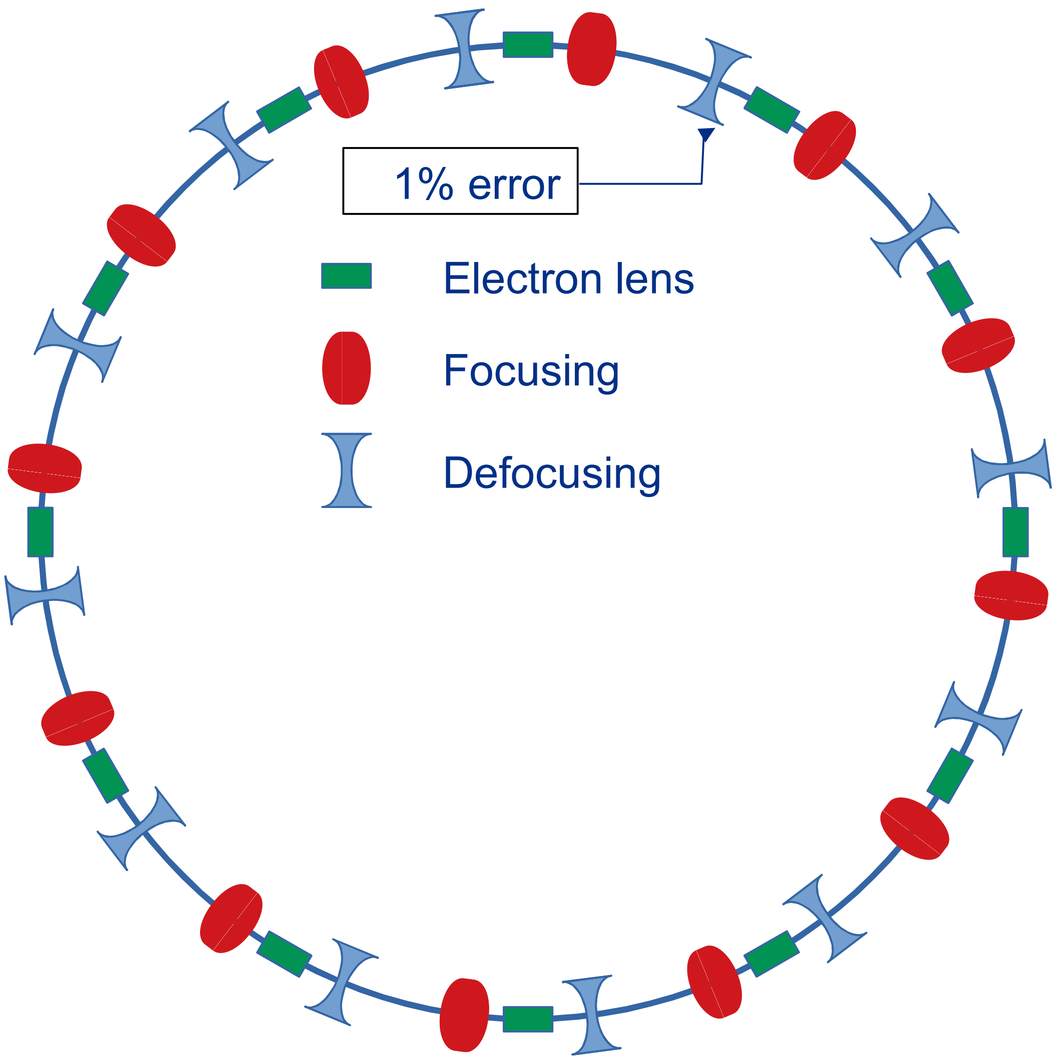


1000 turns

dQ_{SC} = -0.9

Lattice error in one element

Evaluation Plan case #3



1000 turns
$dQ_{SC} = -0.9$
Lattice error in one element
12 e-Lenses

Space Charge Simulators (1)

Synergia

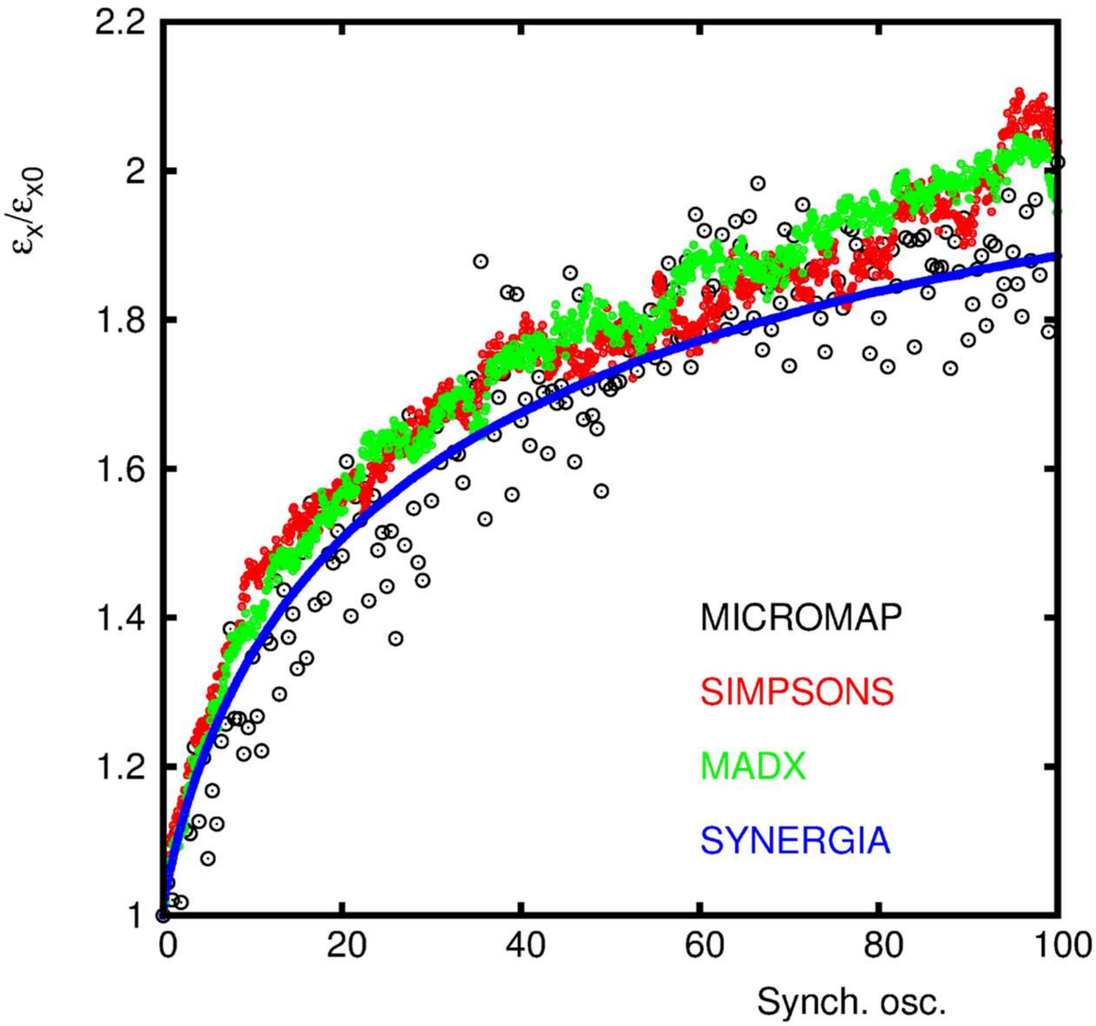
- Developed at Fermilab in the SCD organization.
- Combine beam optics and collective effects.
- Thin electron lens element with longitudinal current modulation added.
- PIC fully self-consistent 3D SC, able to efficiently run millions of macro-particles to reduce statistical noise. All runs performed with 16M macro-particles.
- Macro-particle charge distribution is deposited on a grid. Laplace equation is solved numerically to get potential. Electric field is applied as the space charge kick. 6 SC kicks/cell using split-operator formalism.
- GSI Space Charge Benchmarking
  - F. Schmidt , *et al.*, Code Benchmarking for Long-Term Tracking and Adaptive Algorithms, doi:10.18429/JACoW-HB2016-WEAM1X01
- Landau Damping of Modes
  - A. Macridin, *et al.*, Simulation of transverse modes with their intrinsic Landau damping for bunched beams in the presence of space charge, PRSTAB **18**, 074401 (2015)

Space Charge Simulators (2)

MAD-X SC

- Independent space charge calculations.
- MAD-X space charge upgraded to deal with large space charge.
- Small number of macro-particles (5000), susceptible to statistical effects.
- Beam ∑ matrix calculated by halo-suppressing fitting procedure once/turn.
- ∑ matrix propagated along lattice.
- Space charge kick calculated using the Bassetti-Erskine formula extended for symplecticity with the RMS shape determined by the previously calculated ∑ matrix.

GSI Benchmarking: emittance growth



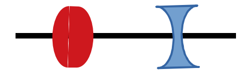
Synergia calculation of emittance growth well agrees with community calculations including MAD-X and frozen models at low SC with long-term tracking.

Credit: Schmidt

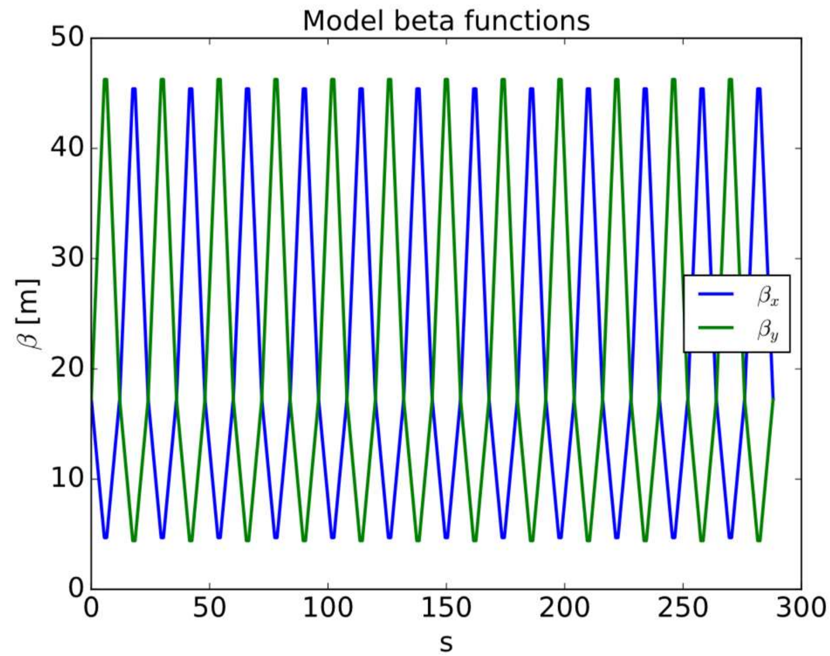
Case #1

How bad is Space Charge by Itself?

Case #1 lattice model



Parameter	Value	unit
length	288.0	m
beam kinetic energy	0.8	GeV
RF frequency	43.814	MHz
slip factor	-0.291186	
x, y chromaticity	-5.68, -5.97	
total RF voltage	6.287	MV
β_x, β_y at lens	17.28, 17.27	m
x, y tunes	3.72, 3.84	
phase advance/cell x, y	111.6°, 115.2°	degrees
synchrotron tune	1/13	
RMS bunch radius	4.15	mm
RMS bunch length	0.5	m
RMS bunch $\Delta p/p$ spread	0.00288	
x, y emittance	1.0005e-6	m.rad
bunch charge	2e11	e
SC tune shift	-0.9	

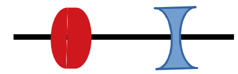


72 SC kicks/turn (6 SC kicks/FODO cell)

Quadrupoles, drifts, RF cavities are linear

Space charge is highly nonlinear

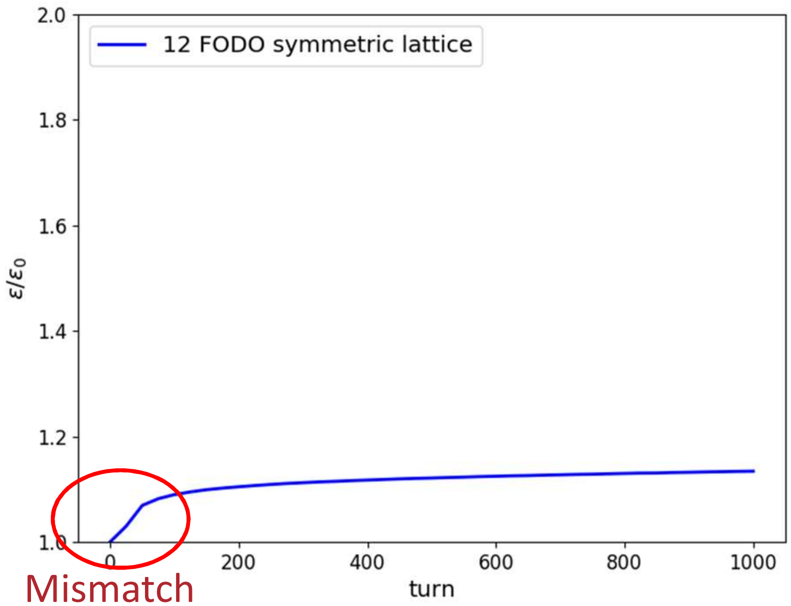
Case #1

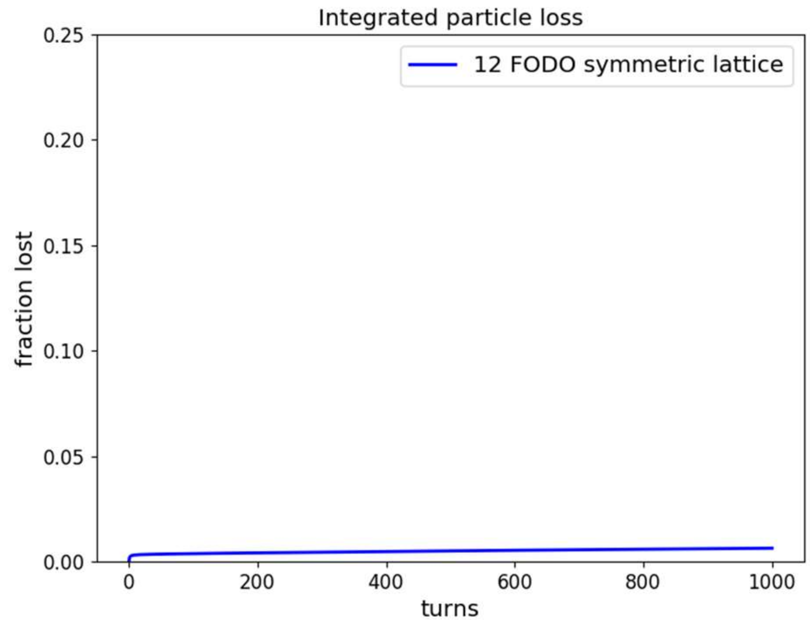


× 12

RMS x emittance growth

4 sigma aperture loss



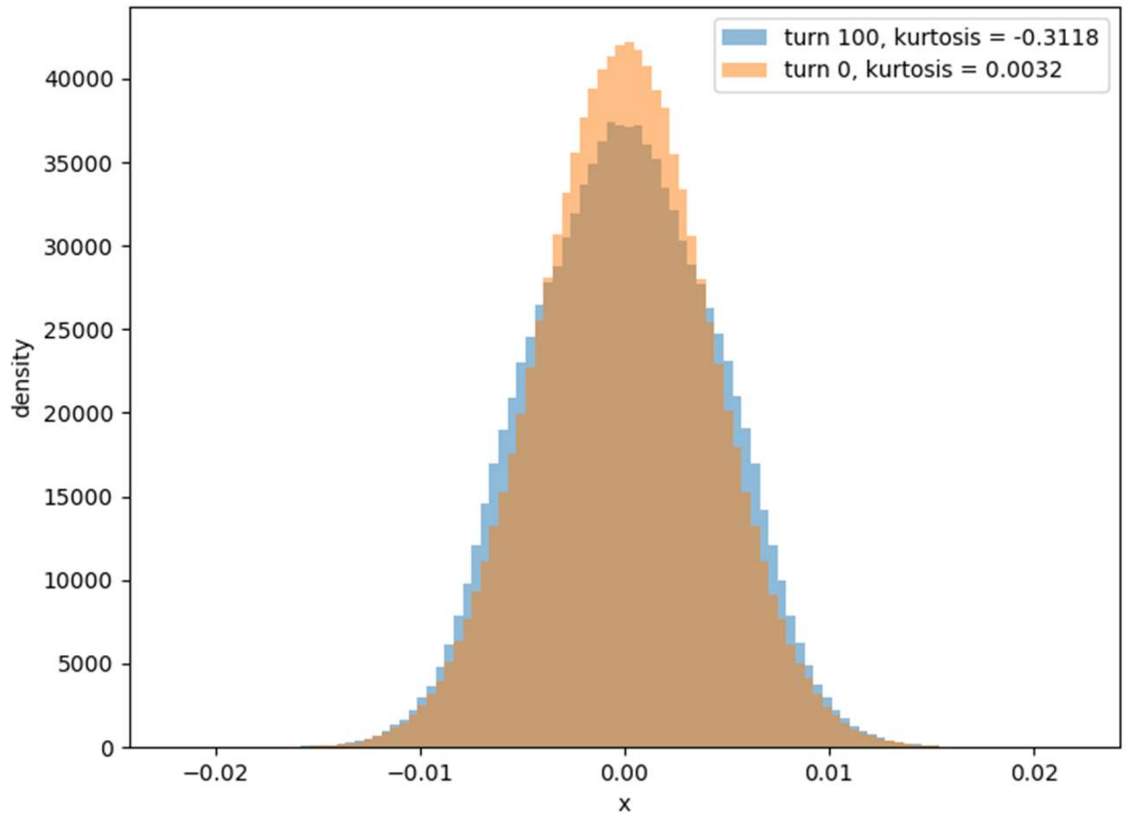


13% emittance growth

0.6% particle loss

No large growth after initial mismatch

Initial mismatch from large space charge

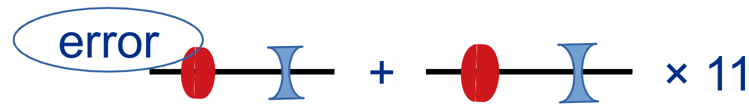


Very large space charge pushes particles out of the core of the Gaussian bunch

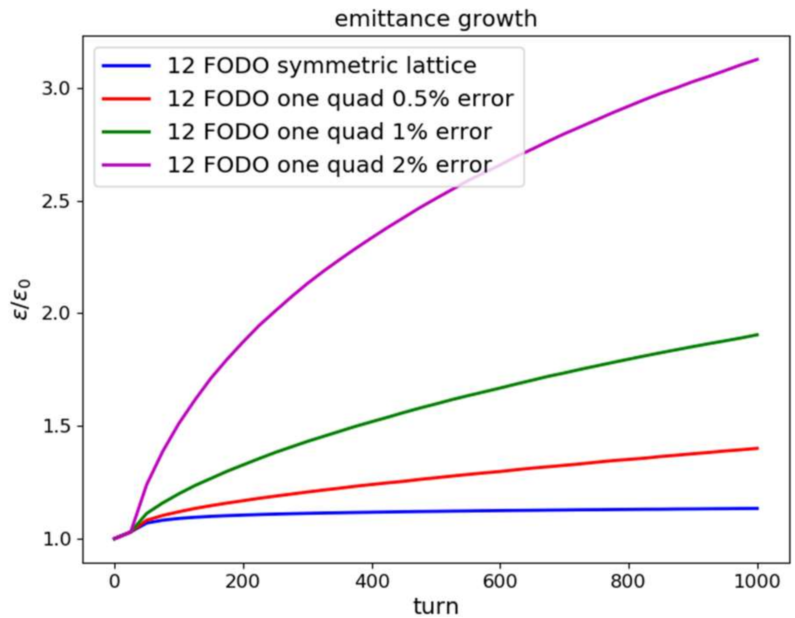
Case #2

Add Lattice Error to Single Element

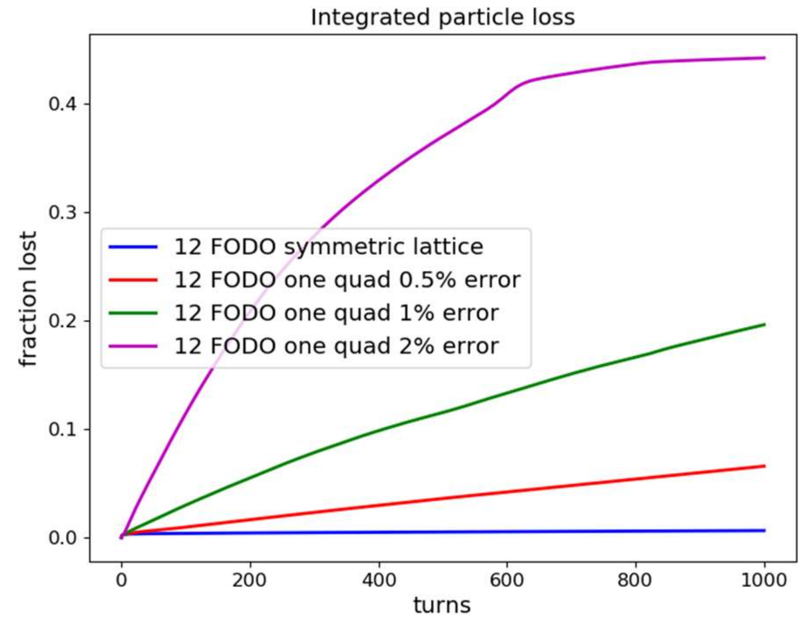
Case #2 element errors



RMS x emittance growth

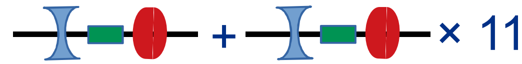


4 sigma aperture loss



Lattice error (%)	Emittance growth (%)	4 sigma loss
0	13	0.6
0.5	41	6.7
1.0	91	19.7
2.0	210	44.5

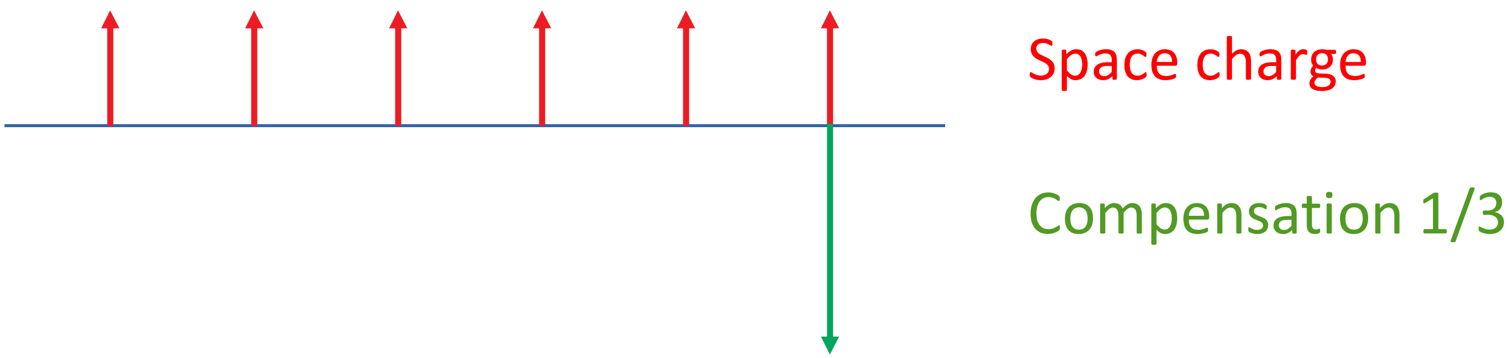
Case #3



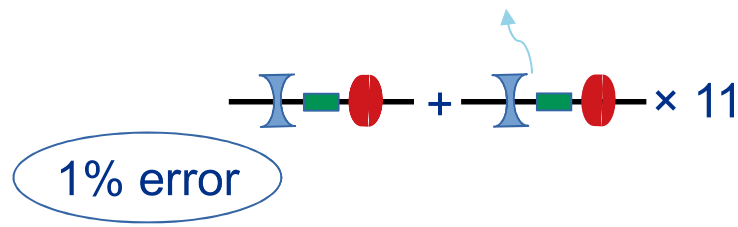
1% error

Add 12 “ideal” compensating lenses

The simulation adds space charge kicks at 72 locations. We simulate a mathematically perfect compensating lens by adding the same space charge kick particle-by-particle multiplied by a negative factor at 12 locations 111° phase advance separation. “Maxwell’s Daemon”



Case #3



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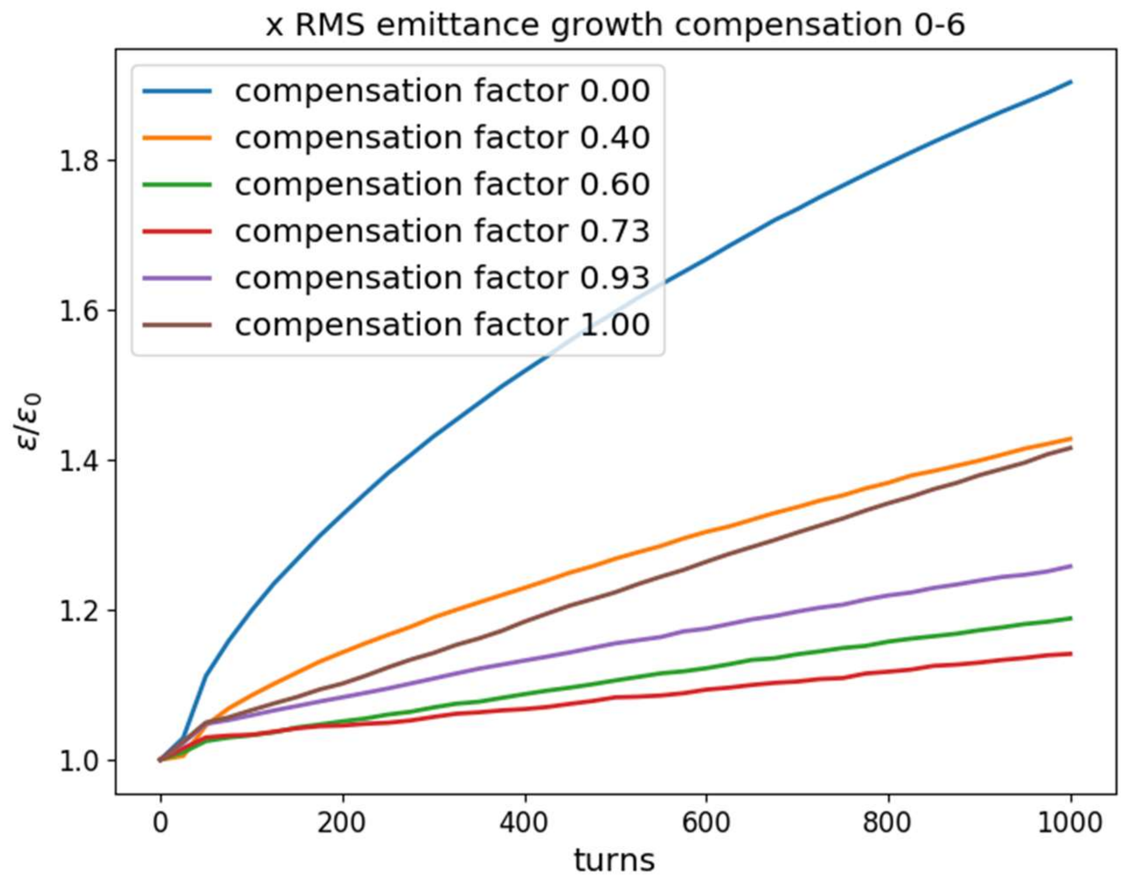
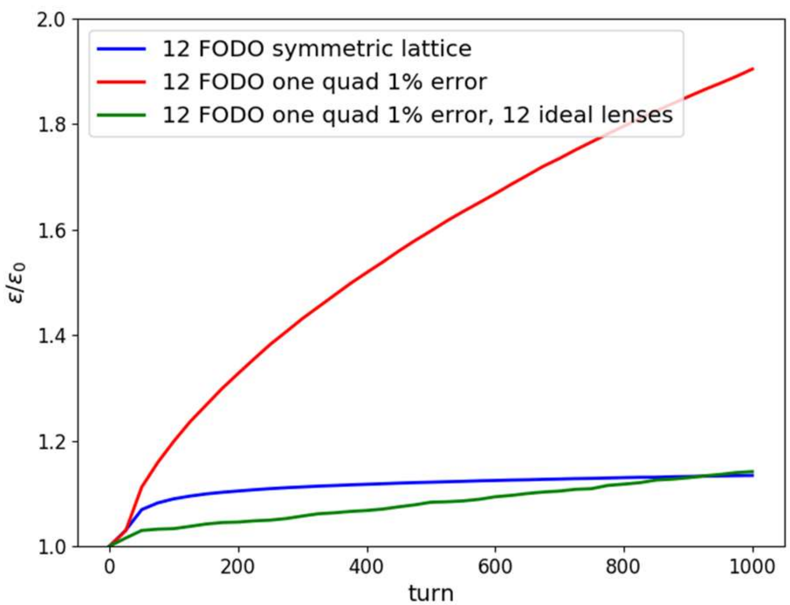


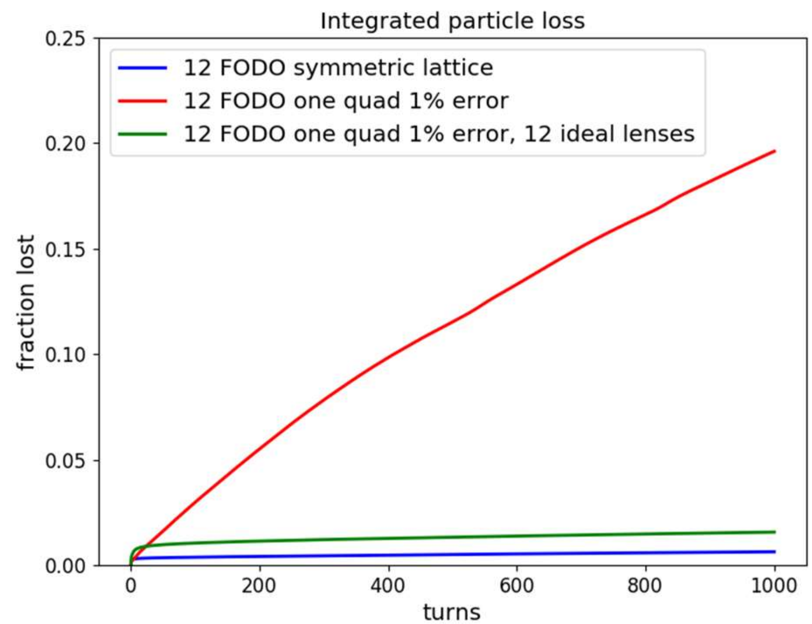
Best compensation occurs at a factor of 0.73 resulting in emittance growth of 14%

Case #3

RMS x emittance growth

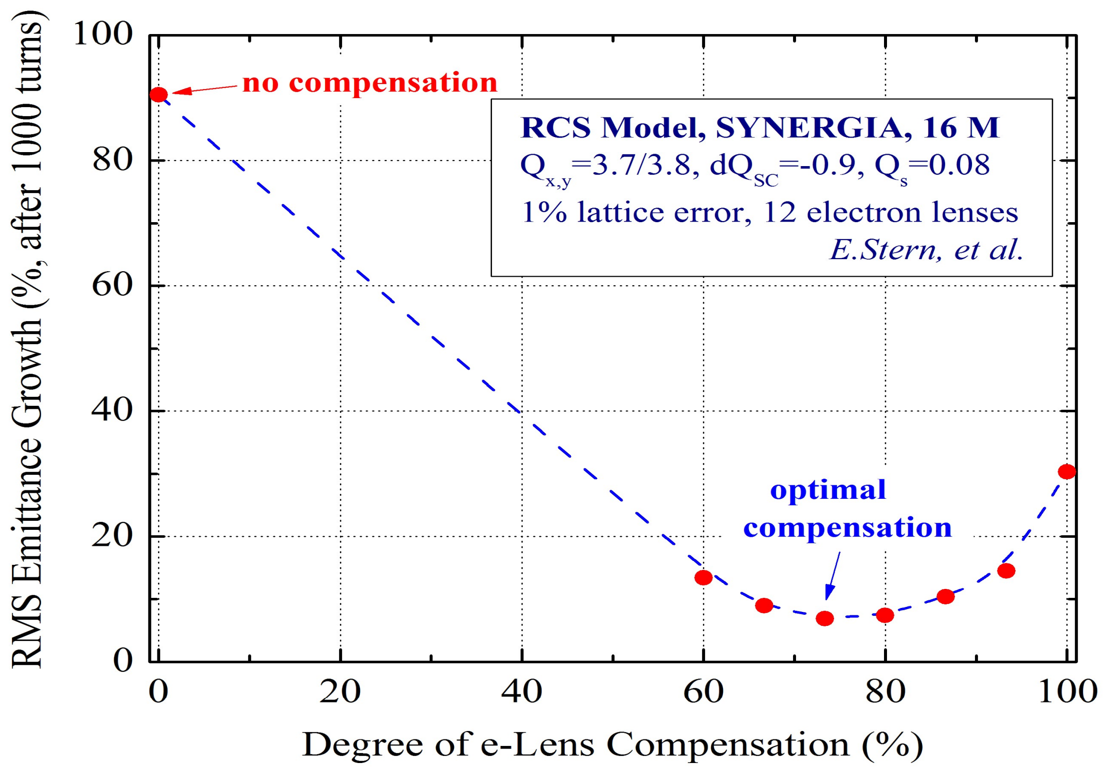


4 sigma aperture loss



	x emittance growth (%)	4 Sigma loss (%)
Case #1 (symmetric)	13	0.6
Case #2 (1% element error)	91	19.7
Case #3 (add 12 optimal lenses)	14	1.5

Case #3 dependence on compensation strength



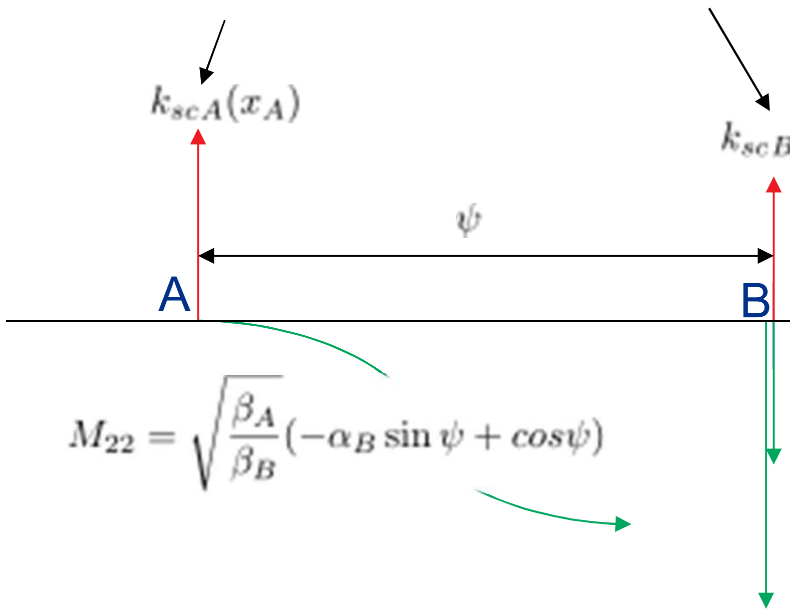
Real world complications

Realization lenses will not perform as well as mathematically optimal lenses.

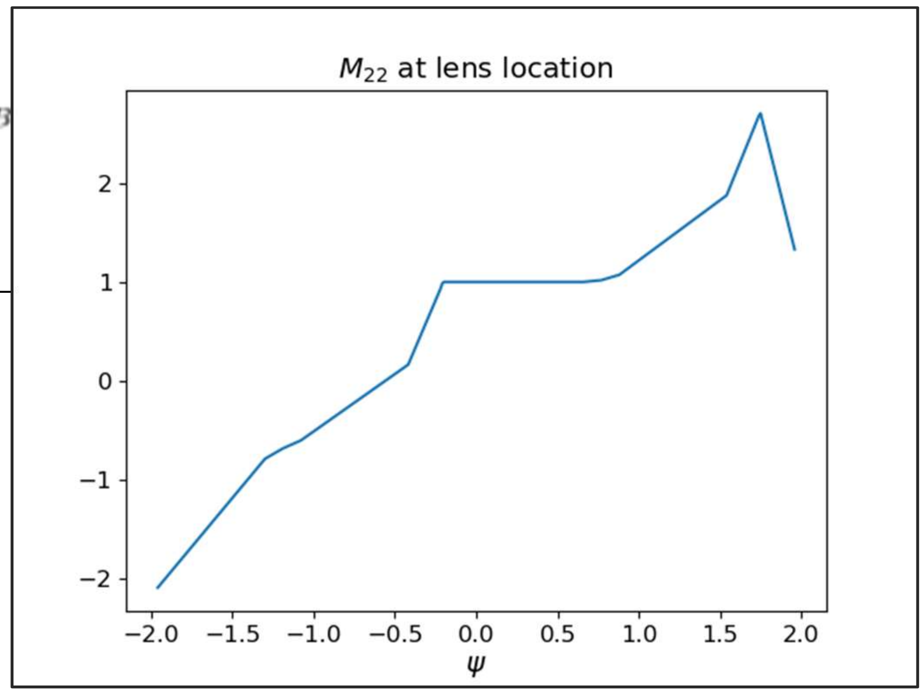
- Dependence on number of lenses
- Mismatch of longitudinal profile

Dependence on number of lenses

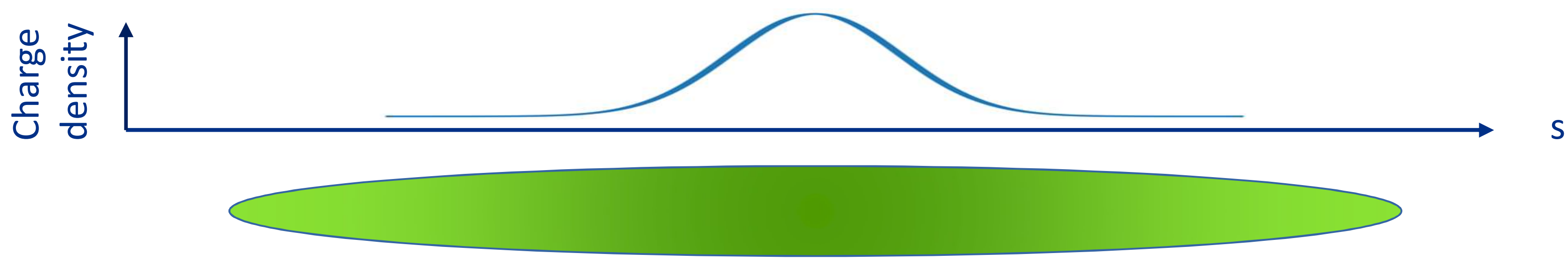
#lenses	X emittance growth (%)
24	6.5
12	13
6	86



$$M_{22} = \sqrt{\frac{\beta_A}{\beta_B}}(-\alpha_B \sin\psi + cos\psi)$$



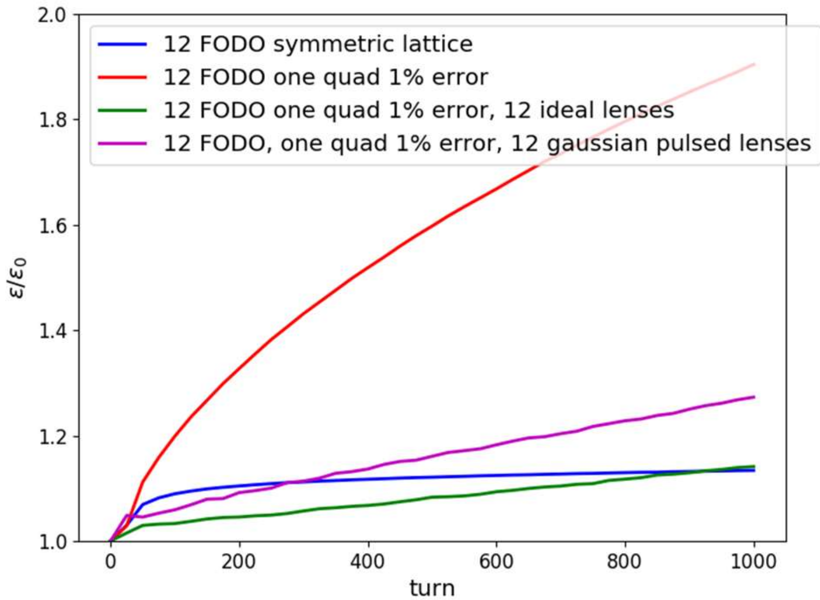
Electron lens profile



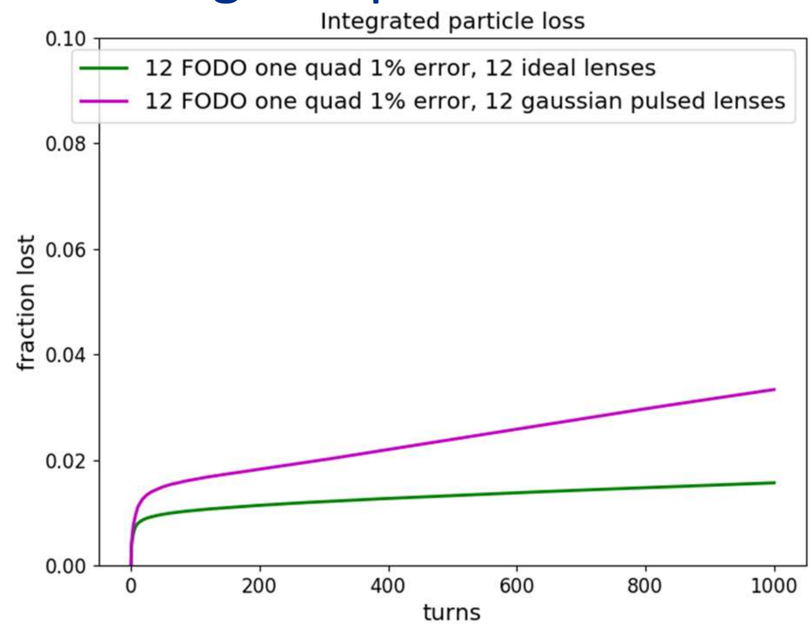
Longitudinal profile	X emittance growth (%)	4 sigma particle loss (%)
DC	60	76
Gaussian	27	3.4

All lens comparison

RMS x emittance growth

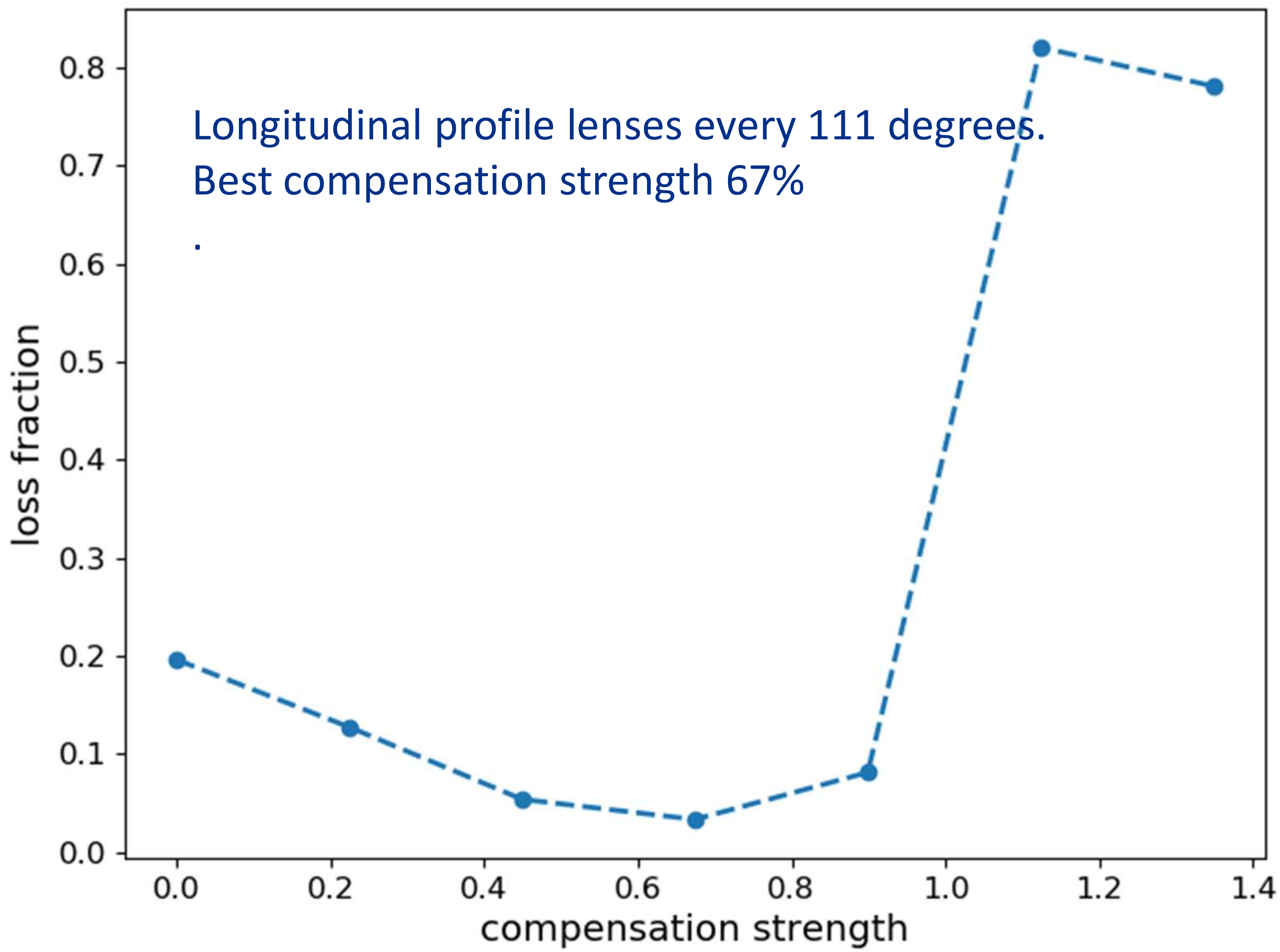


4 sigma aperture loss

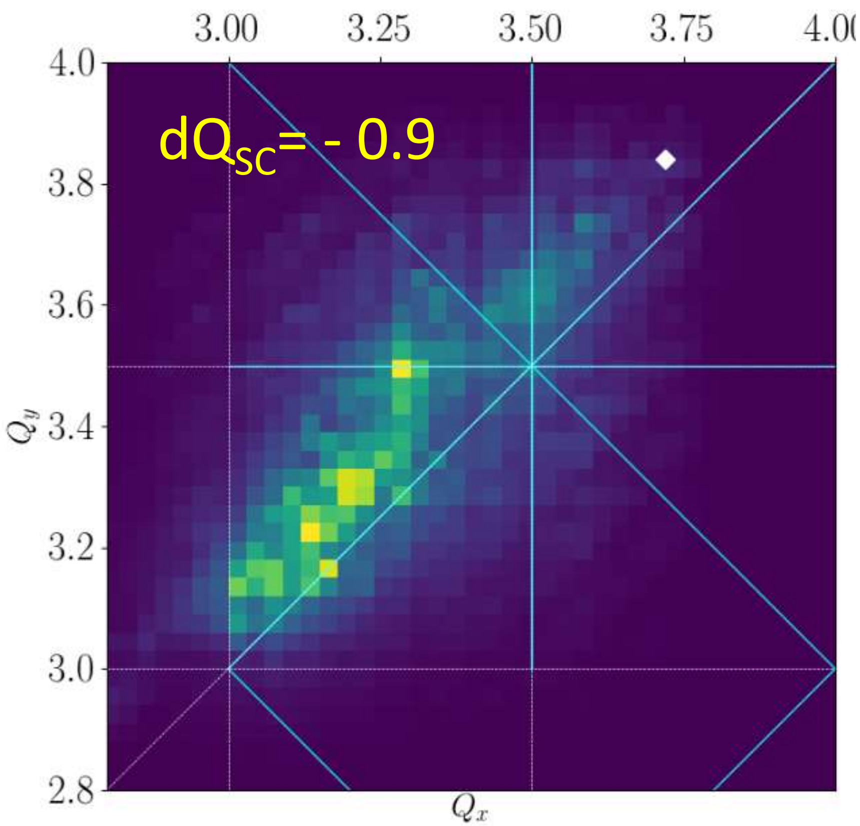


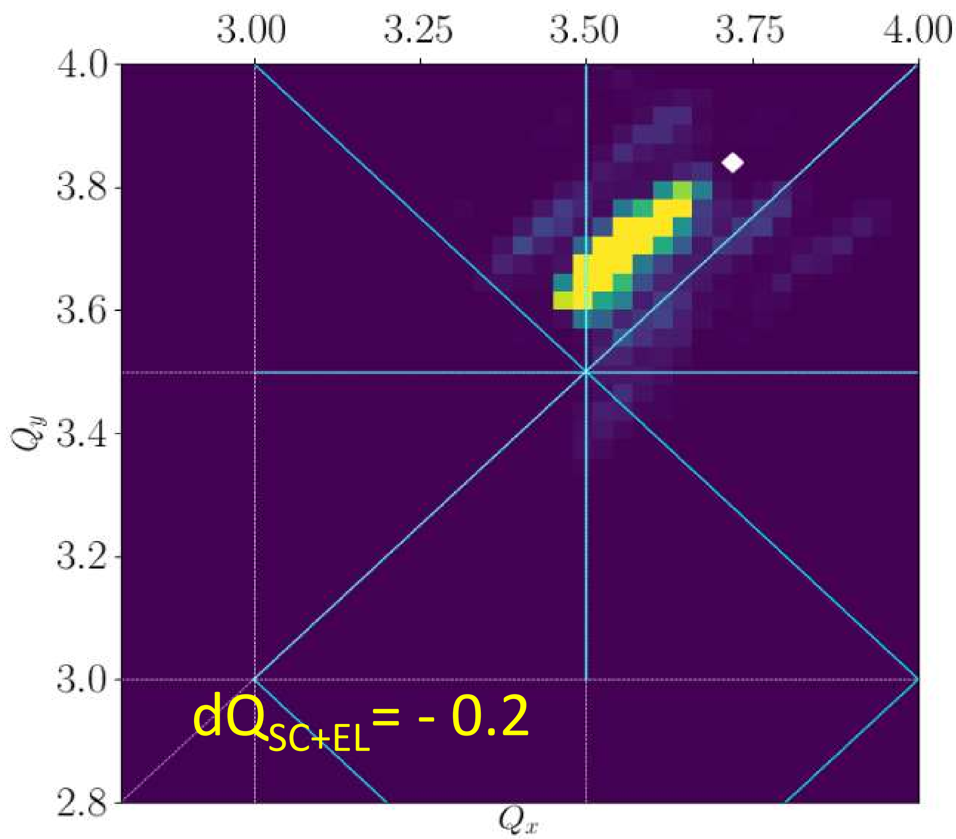
Longitudinal profile	X emittance growth (%)	4 sigma particle loss (%)
12 FODO symmetric	13	0.6
12 FODO one quad 1% error	91	19.7
previous plus 12 ideal lenses	14	1.6
DC lenses	60	76
Gaussian longitudinal lenses	27	3.4

Loss vs. compensation strength



Compensation tune footprints





Summary

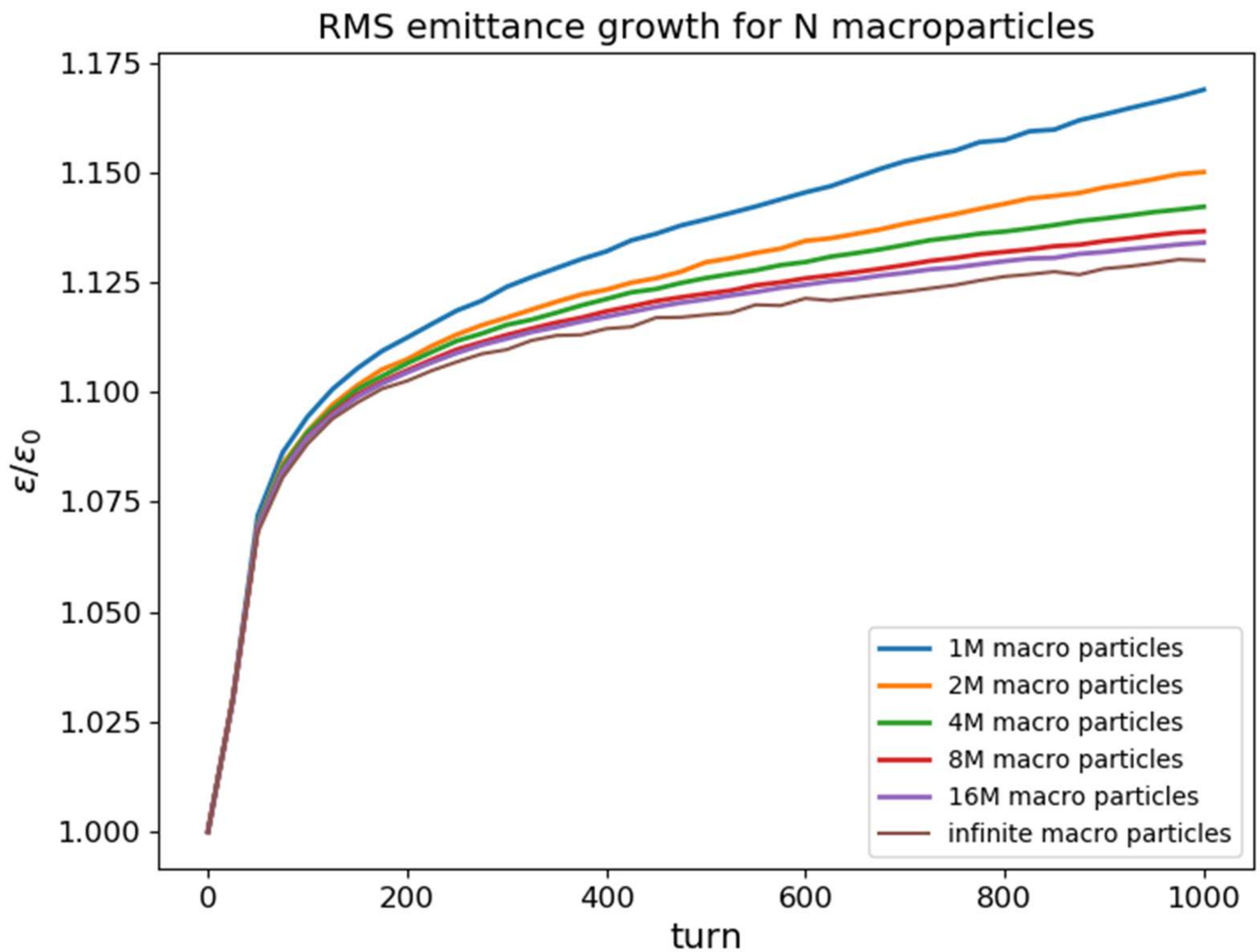
- We have tested Synergia’s space charge simulation at ultimate space charge.
- because of it’s successful simulation of Landau damping.
- 16M particles tracked for statistical noise reduction in calculations of emittance growth and losses.
- Extremely high tune spread simulated.
- Lattice errors are a major contributor to space charge generated beam effects.
- We have demonstrated for the first time in detailed simulations that placement of a sufficient number of electron lenses can substantially ameliorate space charge effects.

Future plans

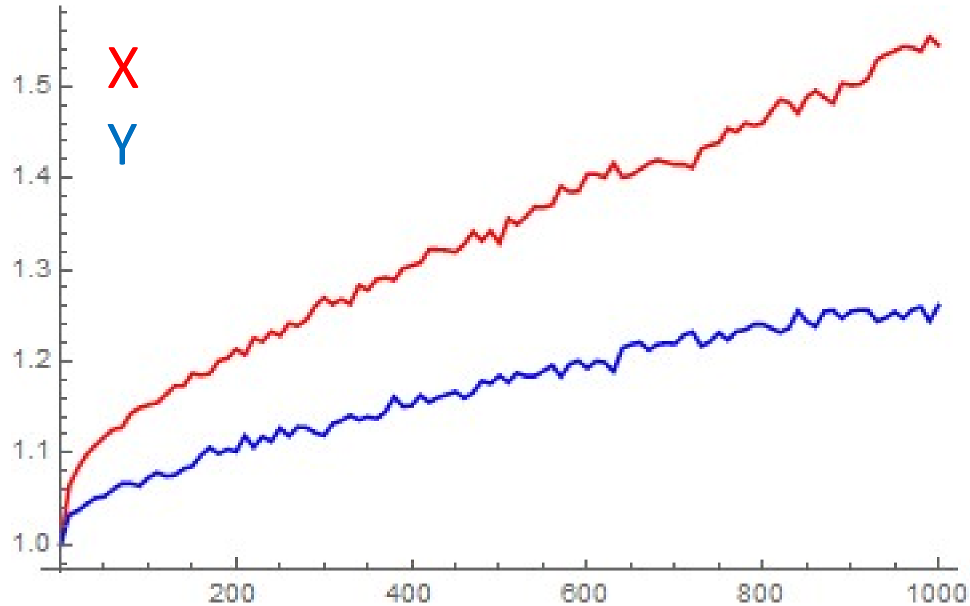
- Different proton bunch distributions may be more beneficial to compensation
  - Longitudinally flat to allow DC lens current
- Adjusting lattice functions might improve lens operation
- Incorporate more realistic lattice including dipoles, sextupoles, dispersion, chromaticity, etc.
- Explore interplay between impedance and space charge

Backup

Sensitivity to the number of macro-particles



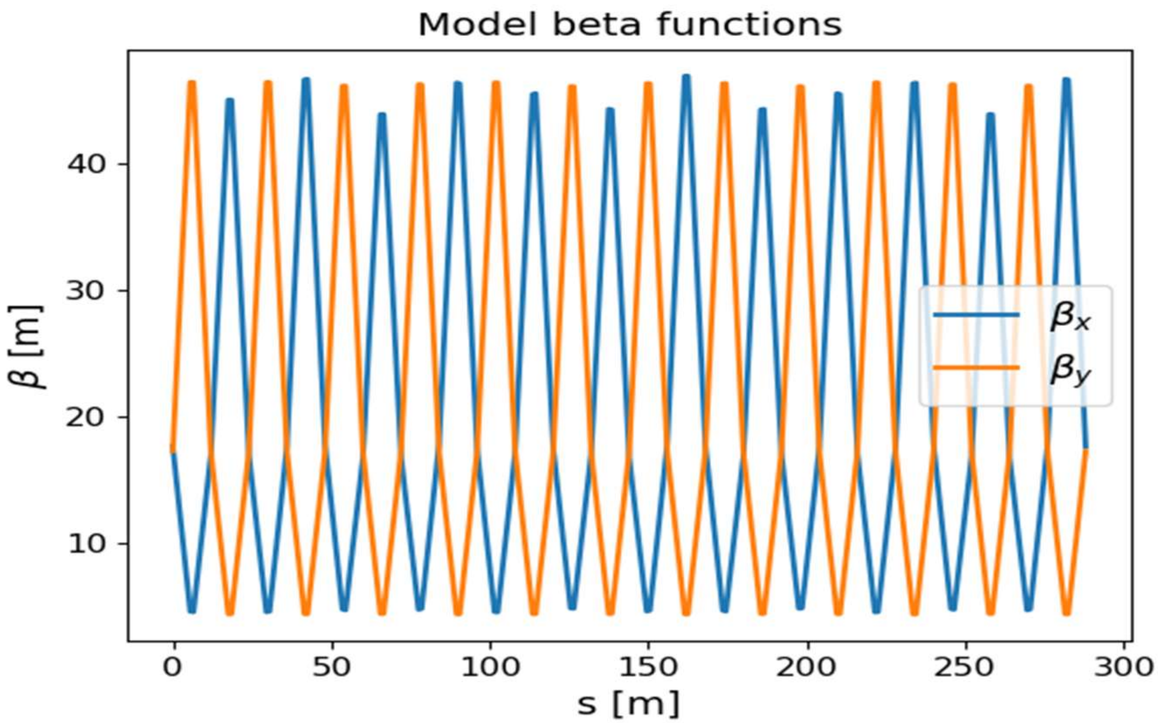
MAD-X SC result with 1% lattice error



RMS emittance growth

- 50% x RMS emittance growth roughly consistent with Synergia's 90%.

Case #2: element errors



Beta beating of ~4%

The Booster runs with beta beating >10%

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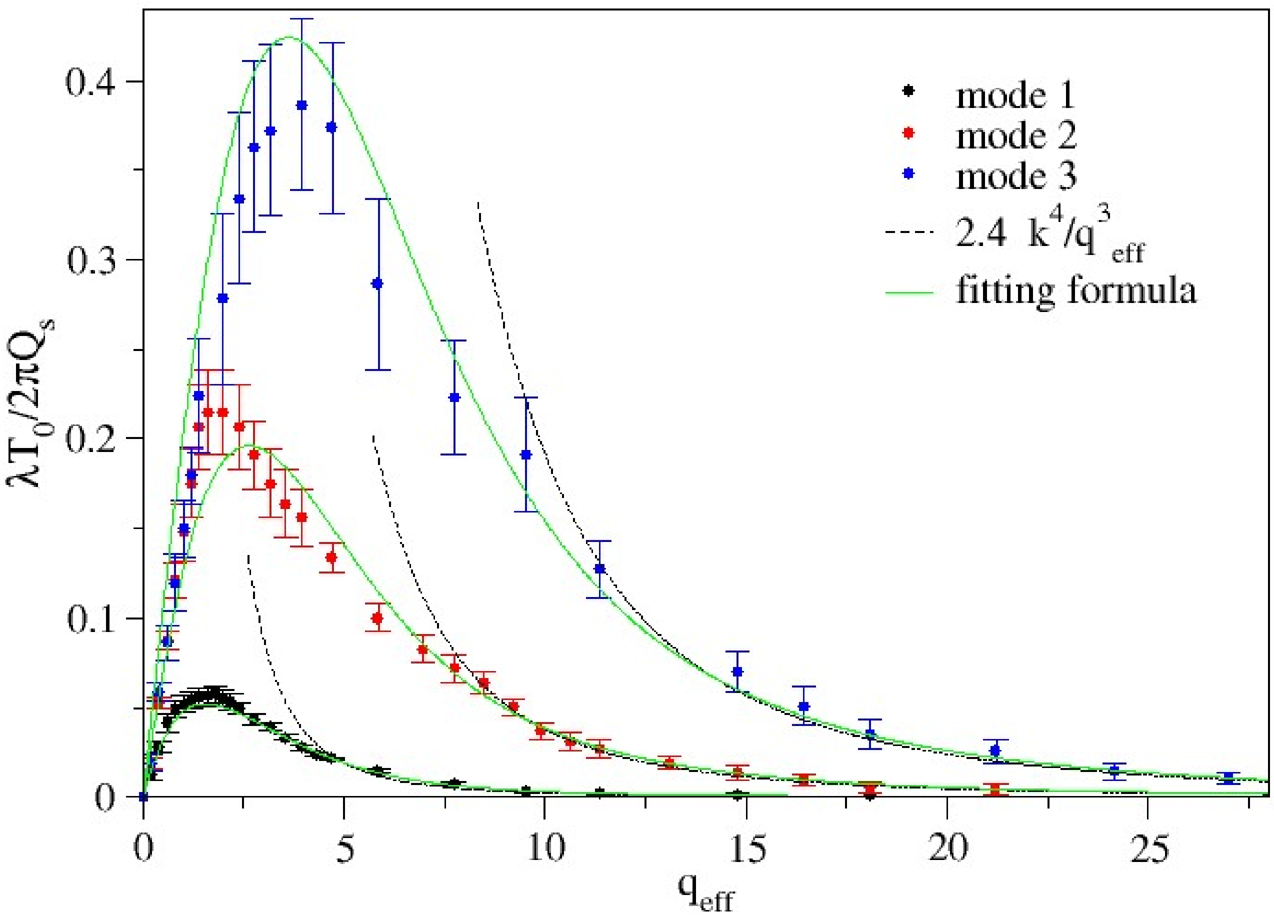
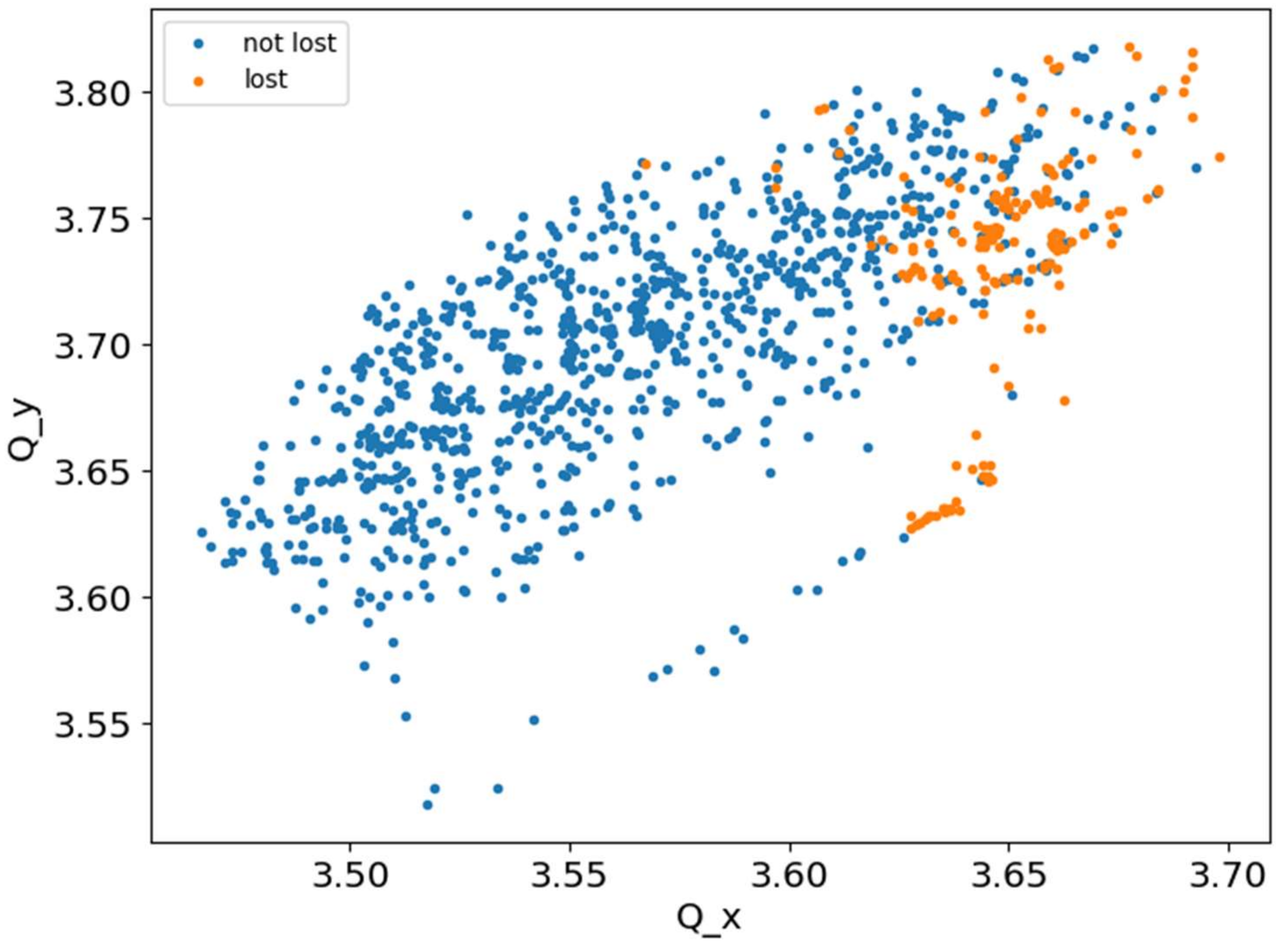
Landau damping



Lost particle tunes



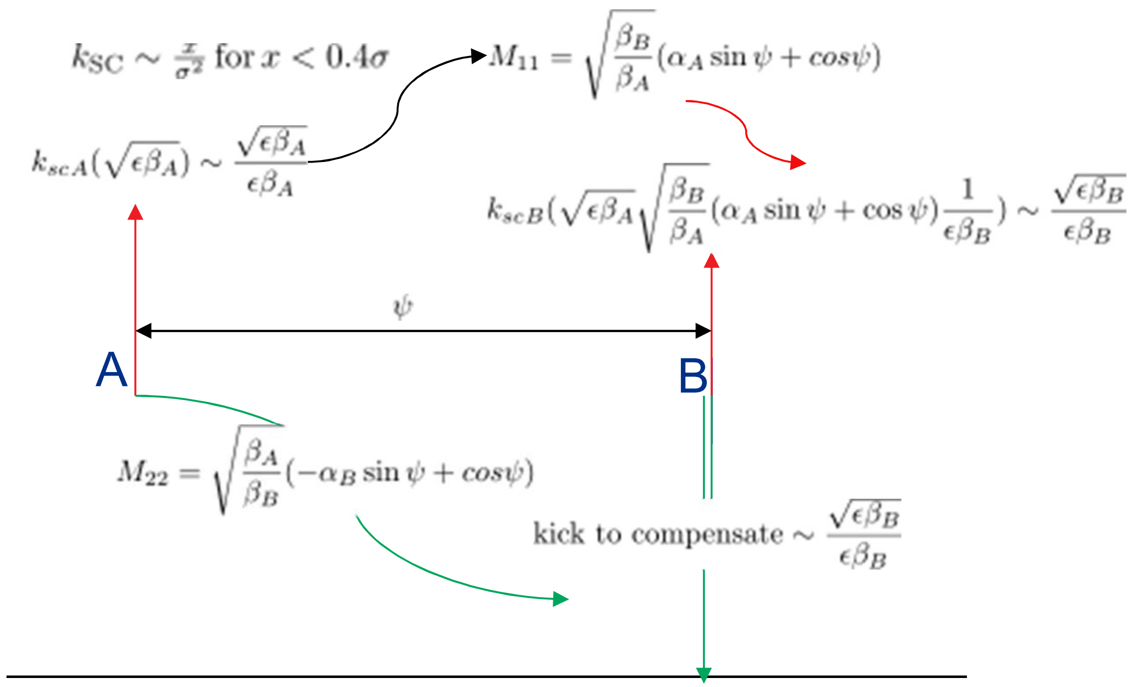
Split operator method for space charge

$$\mathcal{H} = \mathcal{H}_{\text{lattice}} + \mathcal{H}_{\text{SC}}$$

$$\mathcal{M}(\tau) = \mathcal{M}_{\text{lattice}}\left(\frac{\tau}{2}\right)\mathcal{M}_{\text{SC}}(\tau)\,\mathcal{M}_{\text{lattice}}\left(\frac{\tau}{2}\right) + \mathcal{O}(\tau^3)$$

Since space charge in simulation occurs at discrete locations, I can also consider compensation of distributed space charge as compensation of multiple discrete SC kicks.

Compensation for remote space charge



Synergia overview

Self-consistent 6D Particle-in-cell accelerator simulation code

- Specifically designed to simulate combined beam optics and collective effects (space charge and impedance).
- All the usual magnetic elements, RF cavities. Includes detailed septa and apertures for extraction and loss studies
- Now includes electron lens element as a thin lens with longitudinal modulation.
- Collective operations included with beam transport symplectically using the split-operator method.
- PIC space charge solvers available: 2.5D, 3D open boundary, rectangular conducting wall. Semi-analytic: 2D Bassetti-Erskine and linear KV solver.
- Space charge validated with GSI space charge benchmark
- Detailed impedance using a wake functions calculated for particular geometry/composition.
- Multiple bunch beams to investigate coherent bunch modes.
- One or two co-propagating bunch trains.

Synergia overview (cont)

Synergia is actively being used to simulate all the Fermilab machines:

•Fermilab Recycler: Effect of slip-stacking and space charge on losses and evaluation of new operational conditions for optimized running with PIP-II (higher intensity and rep-rate).

•Fermilab Recycler bunch recapture in 2.5 MHz cavities.

•Fermilab Main Injector evaluation of better transition crossing schemes at high rep rates and longitudinal phase space area.

•IOTA propagation with the nonlinear element and understanding effects impacting integrability.

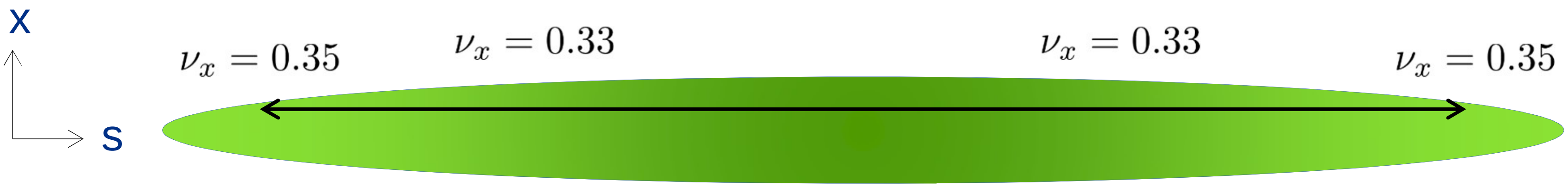
•Landau damping: Alexandru Macridin, *et al*, Parametric Landau Damping of Space Charge Modes, Phys. Rev. Accel. Beams 21, 011004

•RCS replacement for the Booster with integrable optics.

We specialize in multi-bunch, multi-beam, RF manipulation studies.

Note from Monday: includes longitudinal dynamics

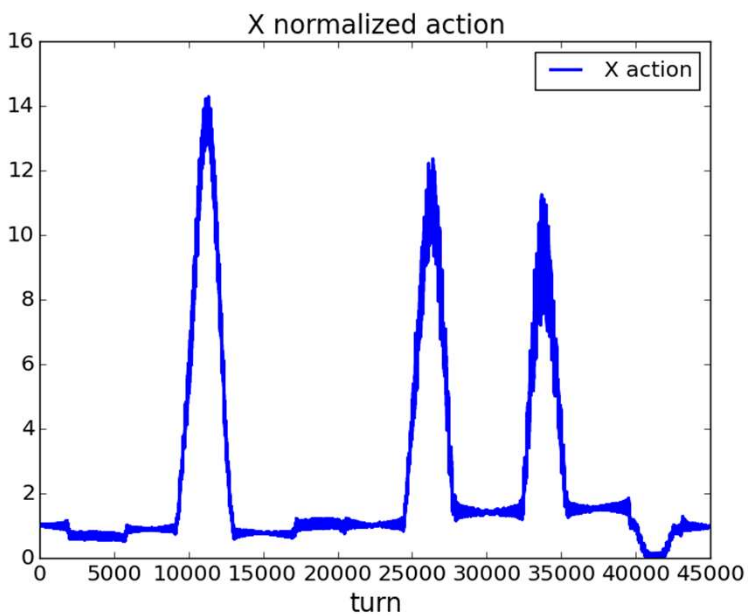
GSI Benchmarking: trapping



Off-axis particle moves through region where space charge tune shift traps it

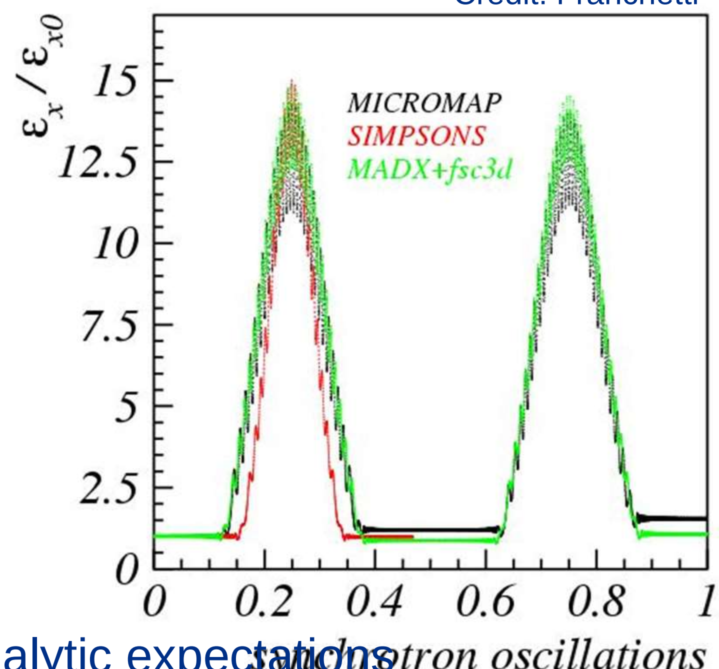
One synchrotron period is 15000 turns

Synergia



others

Credit: Franchetti



Emittance growth matches other codes and analytic expectations

Fermilab

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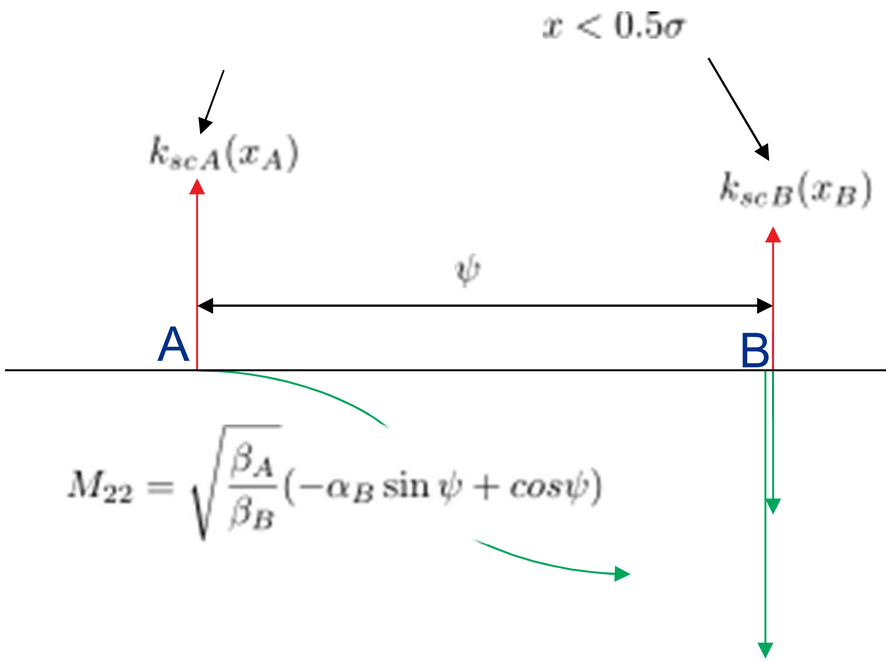
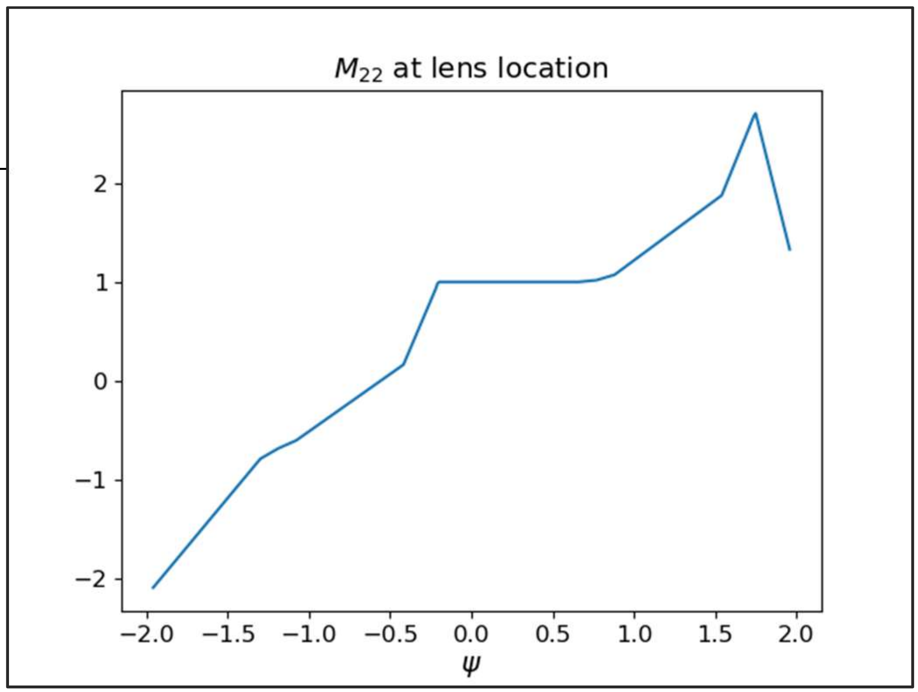
A word about lens separation

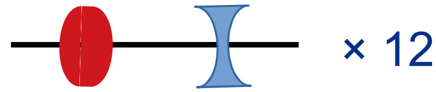




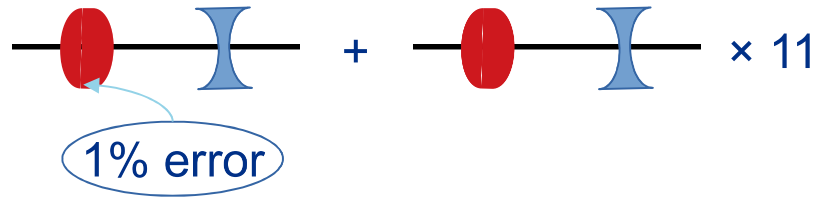
Collaborations / Partnerships / Members 28pt Bold
Logos shown are examples

Evaluation Plan

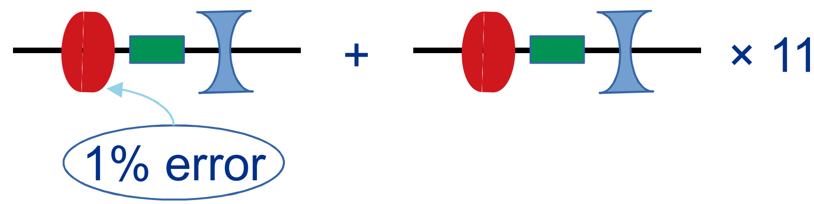
Ideal FODO



FODO with lattice error



FODO with lattice error and
12 lenses



Focusing

Defocusing

Electron lens

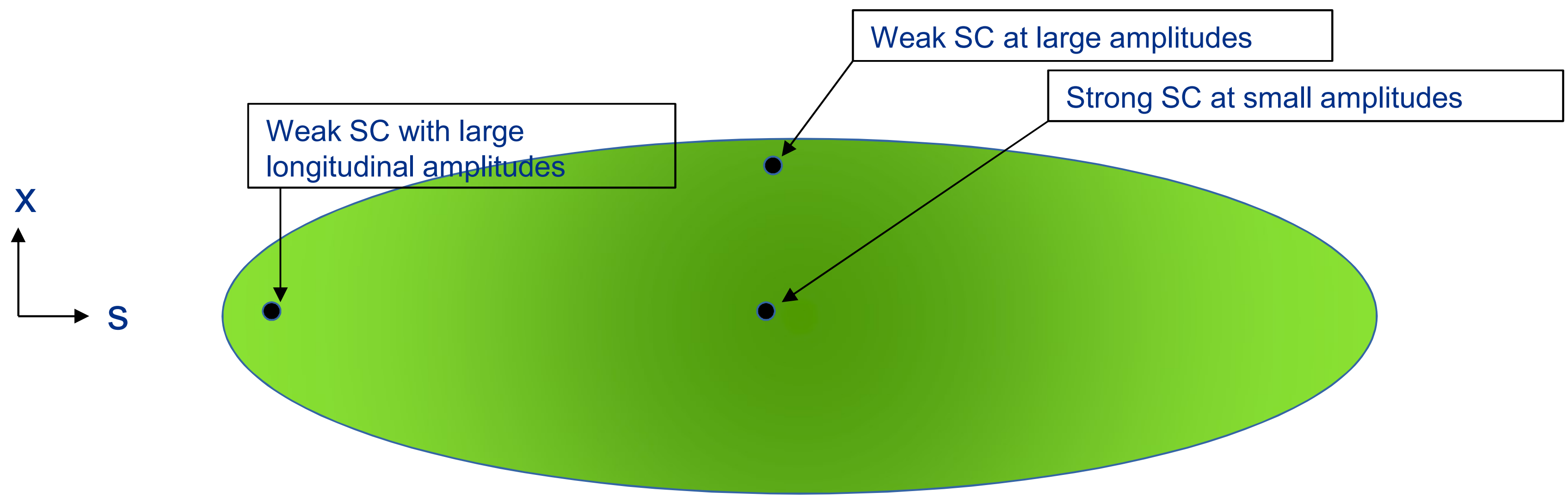
ΔQ_{SC} = -0.9

Initially, avoid complications from bends

Fermilab

12 more realistic lenses (1)

Lenses implemented as thin kicks at 12 locations located where $\beta_x = \beta_y$.



Overcompensation excites resonances and causes emittance growth. Optimal compensation occurs when the electron lens strength is Gaussian transversely and longitudinally to follow the bunch density.